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Reconnaissance geology of the Al Hufayr quadrangle, sheet 27/41A, Kingdom of Saudi Arabia

by

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This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards and stratigraphic nomenclature.

1/ U.S. Geological Survey Saudi Arabian Mission

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Edward A. du Bray[1] and Douglas B. Stoeser[1]

ABSTRACT

The Al Hufayr quadrangle (27/41 A) lies at the northern edge of the Arabian Shield between lat 27°30' and 28°00' N. and long 41°00' and 41°30' E. A cataclastically foliated syenogranite, the oldest rock exposed in the quadrangle, crops out in a restricted area in the south-central part of the quadrangle. Younger, weakly metamorphosed metarhyolite and minor metabasalt, arkosic sandstone, and conglomerate crop out north of the syenogranite and are correlated with lithologically similar rocks exposed to the south that comprise the Hadn formation. Most of the intrusive rocks in the quadrangle are peralkaline or have a peralkaline affinity and are characterized by the presence of soda pyriboles. A large mountain known as Jibal Aja extends into the southeast corner of the quadrangle and is composed of postorogenic peralkaline alkali granite plutons that form concentric rings around a core granophyre. A small plug of Tertiary alkali basalt crops out near the southeast corner of the quadrangle. Eighty percent of the quadrangle is covered by a thick accumulation of eolian sand that forms the southern edge of the An Nafud dune field.

The plutons of the Aja suite represent samples of magma that depict the evolution of a batholith-scale magma body that solidified to the Aja suite. The major- and rare-earth-element chemical variation observed among the components of the suite is a consequence of a discontinuous process that involved chemical evolution via separation of silicate liquid from earlier formed crystals, and emplacement of batches of magma, whose compositions represent stages of the process.

Resource potential in the quadrangle is low. No ancient mines are reported in this quadrangle. Geochemical data for a limited number of pan concentrates of wadi sediment from wadis draining the peralkaline rocks of Jibal Aja show distinctive associations of incompatible lithophile elements. A similar association of elements has previously been shown to be diagnostic of peralkaline granite in the northeast part of the Shield but does not imply high resource potential.

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INTRODUCTION

The Al Hufayr quadrangle covers an area of about 2,740 km^2 and is located between lat 27°30' and 28°00' N. and long 41°00' and 41°30' E. (fig. 1) at the northern edge of the Arabian Shield in the Najd province, Kingdom of Saudi Arabia. Except for local drainage within Jibal Aja, there are no well developed drainage systems within the quadrangle. All of the area within the quadrangle, except its southeast corner, where Jibal Aja is located, has been inundated by the sand of the An Nafud. Scattered inselbergs are emergent through the sand in the southern part of the quadrangle. Elevations range between 850 and 950 m above sea level across the An Nafud in the northern half of the quadrangle and are as much as 1050 m in the southern part of the quadrangle, where the tops of inselbergs are as much as 220 m above the surface of the An Nafud. High points on Jibal Aja, a mountain range characterized by very rugged terrain, are as much as 1500 m above sea level.

The principal settlement in the quadrangle is the village of Al Hufayr located in the south-central part of the quadrangle. Other villages, including Al Hati, Qina, and Umm al Qulban are located in the An Nafud west and north of Jibal Aja. Paved roads connect Al Hufayr, Qina, and Umm al Qulban with Hail, which is located about 36 km by road from the east edge of the quadrangle. Smaller villages and water wells are connected by a network of anastomosing dirt tracks.

The geology of the Al Hufayr quadrangle was first mapped as part of the 1:500,000-scale geologic map of the Northeastern Hijaz quadrangle (Brown and others, 1979). Resource potential in the quadrangle is currently being assessed as part of an integrated mineral potential study that is being conducted in the Hail-Qassim region by the U.S. Geological Survey.

The present report is the result of helicopter-supported geologic mapping conducted during parts of October and December, 1978 and November, 1983 from Hail. The authors wish to thank K.S. Kellogg, who mapped the adjacent Hail quadrangle (sheet 27/41 B) (fig. 1), for helpful discussions and Robert J. Kamilli, who reviewed the report. The authors would also like to thank Ahmed Hamdan al Bazli who performed all modal analyses of the granitic rocks. The work for this report was done by the U.S. Geological Survey in accordance with the work agreement with the Saudi Arabian Ministry of Petroleum and Mineral Resources.

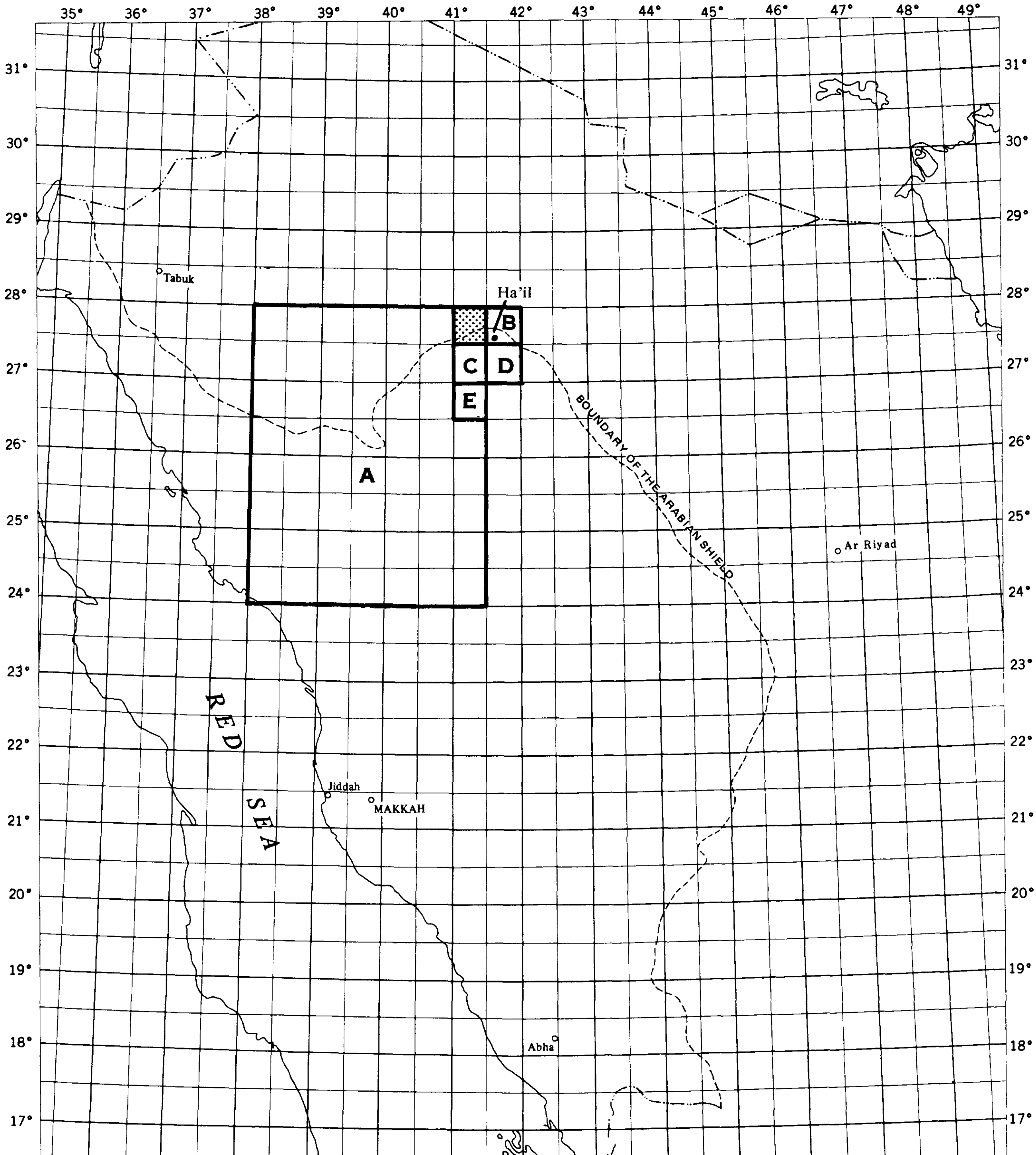


Figure 1.—Index map of western Saudi Arabia showing the location of the Al Hufayr quadrangle (shaded) and quadrangles referred to in the text: A, Northeastern Hijaz (Brown and others, 1979); B, Hail (Kellogg and Stoeser, 1984); C, Al Qasr (Stoeser and Elliott, 1994, unpub. data); D, Qufar (Kellogg, 1983); E, Ghazzalah (Quick, 1983).

PRECAMBRIAN LAYERED ROCKS

Layered rock is volumetrically minor in the Al Hufayr quadrangle. Most of it is composed of rhyolite although minor interbedded basalt, arkosic sandstone, and conglomerate were also identified. All of these rocks were metamorphosed in very low grade conditions. Classification of the volcanic rocks was facilitated by major element chemical analyses (see section on geochemistry and petrogenesis); it is difficult to assign fine-grained rocks such as these to the proper composition group on the basis of petrography.

Hadn formation

A small area in the south-central part of the Al Hufayr quadrangle, approximately centered on Jabal Khasab, is underlain principally by porphyritic rhyolite flow rock and crystal-lithic rhyolite ash flow tuff (hv) of the Hadn formation that also includes minor conglomerate, mafic metavolcanic rock, and arkosic silt and sandstone (hs). These rocks crop out in isolated inselbergs emergent through the sand of the An Nafud so that stratigraphic relations and thickness estimates are obscured.

The layered rocks exposed in the Al Hufayr quadrangle are considered to be correlative with lithologically similar rocks that are exposed in a large area to the south and west and are included in the Hadn formation (Kellogg, 1983; Quick, 1983; and Stoeser and Elliott, 1984, unpub. data. These rocks represent extrusion of a large volume of silicic volcanic material within a major volcanic province. Geologic mapping in the northeastern Arabian Shield shows that the rocks of the Hadn formation are younger than either the greenstone of the Nuf formation (Kellogg, 1983) or Banana greenstone (Quick, 1983), exposed in adjacent areas. The Hadn formation rocks are not in contact with intrusive rocks in the Al Hufayr quadrangle, but age relations with similar rocks in adjacent quadrangles suggest that rocks of the Hadn formation are older than the postorogenic alkali-feldspar and alkali granites, younger than the cataclastically foliated syenogranite, and may be approximately coeval with the remainder of the intrusive rocks in the quadrangle. The thickness of the Hadn formation rocks in the Al Hufayr quadrangle cannot be estimated but Chevremont (1982) indicates a minimum thickness from 3 to 5 km.

The porphyritic rhyolite includes between 10 and 15 percent phenocrysts of quartz and potassium feldspar; phenocrysts of both are rounded and resorbed and the potassium feldspar phenocrysts are weakly sericitized. The phenocrysts are as much as 2 mm in diameter and are set in a devitrified matrix composed of very fine grained quartz and alkali feldpar. The groundmass also includes trace amounts of opaque oxides and biotite.

The tuffaceous rocks are very poorly sorted and clasts of quartz, feldspar, and lithic fragments are angular. The degree of welding in the crystal lithic tuff ranges from weak to very dense. Fluidal layers in the more strongly welded tuffs contain abundant very fine grained devitrified ash intergrown with anhedral aggregates of greenish biotite. Opaque oxides grains, as much 0.5 mm in diameter, are more abundant in the tuffs than in the flow rocks. The tuffs contain exotic crystals of quartz, albite, and microcline as well as lithic fragments composed of fine-grained, trachytic, plagioclase-porphyritic andesite. Anhedral grains of metamorphic epidote, as much as 0.2 mm in diameter, form 1 to 2 percent of the welded tuffs.

Minor amounts of basalt and andesite were found interbedded with the more felsic volcanic rocks at the north end of Jabal Khasab. The andesite is spectacularly porphyritic; it contains flow-oriented euhedral laths of weakly sericitized plagioclase as much as 15 mm long. The phenocrysts are set in a groundmass composed of intergranular plagioclase and opaque oxides with minor anhedral epidote. The basalt is also porphyritic. Blocky phenocrysts of sericitized plagioclase, as much as 0.4 mm long, form about 3 percent of the rock and are set in an intergranular matrix composed of very fine grained anhedral plagioclase, hornblende, and opaque oxides. Anhedral crystals of epidote, as much as 0.1 mm in diameter, form about 5 percent of the basalt.

South of Jabal Khasab medium to coarse sandstone and conglomerate (hs) are interbedded with the volcanic rocks of the Hadn formation. The sandstone is arkosic and consists of thinly bedded, poorly sorted aggregates of angular quartz, microcline, and volcanic lithic fragments. The grain size of the sandstone ranges from 0.1 mm to about 0.8 mm. Intergranular red-brown biotite forms between 5 and 10 percent of most samples. Trace amounts of epidote, opaque oxides, and albite were also identified. The conglomerate consists of a poorly sorted deposit that contains rounded clasts as much as 20 cm in diameter that are principally composed of felsic metavolcanic rock but also includes clasts of granitic rock, including monzogranite and alkali-feldspar granite.

PRECAMBRIAN INTRUSIVE ROCKS

Plutonic rock crops out primarily in the southeast corner of the quadrangle but also forms many of the isolated inselbergs that are located throughout the southern part of the quadrangle. Intrusive rock was divided into plutons on the basis of mapped and inferred contacts, characteristic composition (fig. 2A-C), textural features, relations with adjacent rock, dikes, and structural features. Plutonic rock nomenclature follows the guidelines of Streckeisen (1976). The contents of plagioclase, quartz, and potassium feldspar given for each of the intrusive units are averages of stained slab modal data for the samples collected. Biotite-amphibole-pyroxene ratios are visual estimates based on thin section examination. Age relations, based on dike density and truncation of dikes by plutons, degree of pluton deformation, and geometric relations, indicated for plutons not exposed in Jibal Aja are tentative because of extensive surficial deposits and the lack of exposed contacts.

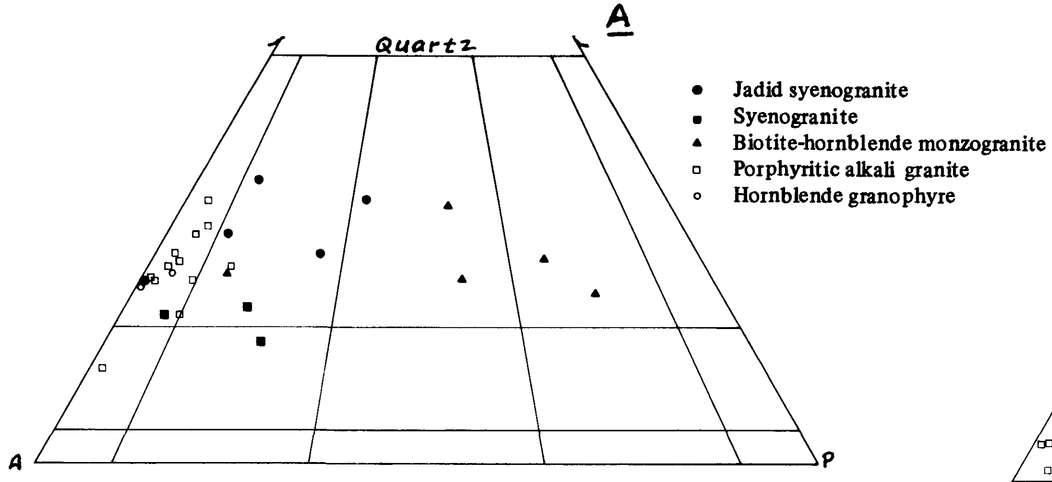
The number of peralkaline or peralkaline tending plutons in the Al Hufayr quadrangle is noteworthy. In particular, Jibal Aja is an intrusive suite composed of peralkaline alkali granite plutons that form concentric rings around nearly peralkaline core granophyres. The intrusive history and intrusive relations within this complex are complicated and suggest that all of the plutons are approximately coeval. Several less evolved, probably older, plutons crop out west of Jibal Aja and are similar to calc-alkaline intrusive rock that underlies much of the Arabian Shield (Schmidt and Brown, 1982).

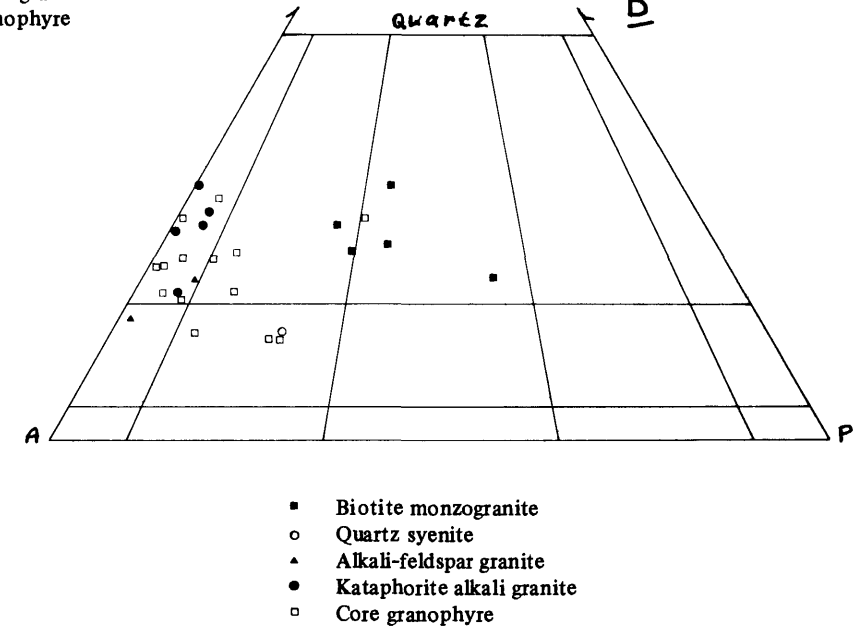
Other intrusive rocks

Jadid syenogranite

An area of at least 25 km^2 in the southcentral part of the quadrangle is underlain by a grayish, orange-pink syenogranite. This pluton is herein informally named the Jadid syenogranite (jsg) for prominent exposures of this lithology encountered at Jabal Jadid. Outcrops of this pluton form isolated inselbergs that are emergent through sand of the An Nafud.

The syenogranite (fig. 2A) is characterized by a cataclastic foliation and a lineation. It is hypidiomorphic inequigranular. Its felsic constituents are plagioclase, quartz, and microcline (12, 34, and 52 percent, respectively). Anhedral microcline crystals, as much as 5 mm long, are perthitic. Quartz grains are recrystallized into fine-grained homogeneous domains with an average grain size less than 0.5 mm and forms gneissic segregation bands. Biotite has been completely recrystallized to anhedral yellow-brown aggregates, as much as 10 mm long, that are parallel to quartz segregations and account for about 2 percent of the rock. Trace amounts of fine-grained, anhedral opaque oxides, aegerine-augite, albite, zircon, and fluorite were also identified. The Jadid syenogranite is the only lithology in the Al Hufayr quadrangle characterized by a well developed cataclastic texture. It is regarded as the oldest unit in the quadrangle and indicates a major, early deformational event of regional extent.





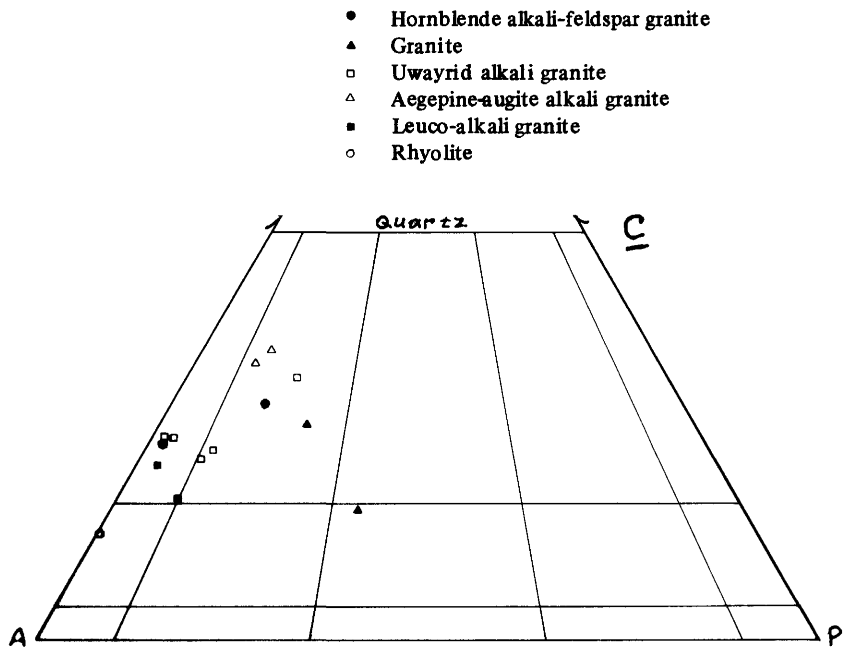


Figure 2.—Quartz-alkali feldspar-plagioclase (QAP) ternary diagram (Streckeisen, 1976) showing the modal composition of intrusive rocks in the Al Hufayr quadrangle; the sum of Q, A, and P is normalized to 100 percent. Each plotted point represents a modal analysis (between 400 and 700 points counted on a stained slab measuring at least 50 cm^2) for a single sample. Albite is counted as plagioclase for samples of the alkali and alkali-feldspar granites and for the granophyres so that the ratio of albite to potassium feldspar is discernible. Properly plotted modes for these samples would fall on the quartz-alkali feldspar sideline of the ternary diagram.

Syenogranite

Several isolated hills around and including Jabal Saq in the southwest part of the quadrangle are underlain by a pluton composed of moderate orange-pink syenogranite (sg). The syenogranite pluton may extend into the northwestern part of the adjacent Al Qasr quadrangle where a large area is underlain by a lithologically similar rock (Stoeser and Elliott, 1984, unpub. data).

The syenogranite (fig. 2A) is medium grained, allotriomorphic equigranular, and is characterized by a weakly developed cataclastic texture. Its felsic constituents are albite, quartz, and potassium feldspar (14, 18, and 63 percent, respectively). Albite forms rare, stubby laths as much as 0.8 mm long. Quartz is anhedral and forms grains as much as 3 mm in diameter, although in deformed samples it is recrystallized to anhedral aggregates composed of individual grains not greater than 0.5 mm in diameter. Potassium feldspar forms anhedral to subhedral grains, as much as 3.5 mm in diameter, that display both Carlsbad and gridiron twinning. The potassium feldspar is characterized by well developed lamellar perthitic exsolution. Anhedral grains of hornblende as much as 3 mm long are pleochroic from pale yellowish brown to moderate green and compose about 5 percent of the rock. Trace amounts of opaque oxides, allanite, biotite, and fluorite were identified. The opaque oxides are anhedral and are commonly associated with hornblende. Biotite appears to be a reaction product of hornblende. Allanite forms as much as 1 percent of some samples. The cataclastic deformation seen in this rock type is much less well developed than in the Jadid syenogranite.

Biotite-hornblende monzogranite

A series of inselbergs, elongate in the east-west direction, and located northwest of Jabal Khasab are underlain by light-gray monzogranite (bhm). The hills underlain by this lithology are noteworthy in that they are penetrated by a very closely spaced set of dikes that trend east-west. In many outcrops dikes are volumetrically more abundant than the host rock.

The monzogranite (fig. 2a) is coarse grained, allotriomorphic granular, porphyritic, and compositionally inhomogeneous; its composition ranges between syenogranite and granodiorite. Its felsic components are plagioclase, quartz, and potassium feldspar (37, 28, and 29 percent, respectively). Quartz occurs in weakly recrystallized grains as much as 5 mm in diameter. Optically continuous domains within the recrystallized grains are as much as 3 mm in diameter. Subhedral phenocrysts of perthitic potassium feldspar are as much as 1.5 cm long. Plagioclase forms weakly zoned anhedral laths as much as 3 mm long. Color index is 6 and the biotite- hornblende ratio is about 2:1. Biotite forms anhedral to subhedral aggregates as much as 3 mm in diameter and is pleochroic from yellow brown to reddish brown. Hornblende forms subhedral laths as much as 3 mm long and is pleochroic from yellow-green to pale-bluish green. Trace amounts of opaque oxides, zircon, apatite, and sphene were observed. The opaque oxides form anhedral grains as much as 0.5 mm in diameter. Zircon is especially abundant as inclusions in biotite in some samples.

Biotite monzogranite

Xenolithic blocks of biotite monzogranite (mgb) crop out at several isolated localities within the rocks of the Aja suite and probably represent roof or country rocks into which the magmas represented by the Aja suite were emplaced.

The biotite monzogranite (fig. 2B) is light gray, medium grained, and hypidiomorphic inequigranular. Its felsic components are plagioclase, quartz, and potassium feldspar (26, 28, and 44 percent, respectively). Grains of quartz and the feldspars range between 1 and 3 mm in diameter; all are anhedral to subhedral. The feldspars are weakly altered to sericite and quartz grains are weakly recrystallized. Biotite is pleochroic from pale yellow to greenish brown, occurs in anhedral aggregates as much as 0.4 mm in diameter, and forms about 2 percent of the rock. Trace amounts of hornblende, opaque oxides, sphene, zircon, apatite, and allanite were identified.

Gabbro

An area of about 2 km^2 located near the northwest margin of Jibal Aja is underlain by dark-gray gabbro (gb). Like the biotite monzogranite, the gabbro is considered to be a roof pendant within the rim granites of the Aja suite. The gabbro is medium grained and hypidiomorphic inequigranular. Unzoned, subhedral laths of albite-twinned plagioclase form about 60 percent of the rock. Very fine grained anhedral aggregates of uralite, after hornblende, occur in subhedral laths as much as 5 mm long and form about 35 percent of the rock. Biotite occurs in anhedral aggregates composed of crystals that are pleochroic from very pale brown to reddish brown and compose about 2 percent of the rock. Opaque oxides occur as anhedral grains and compose about 3 percent of the rock.

The gabbro, biotite monzogranite, biotite-hornblende monzogranite, and syenogranite are considered to be approximately coeval. They occur as xenolithic blocks within the rocks of the Aja suite, are intruded by dikes, and several are typified by cataclastic textures. These features, in the absence of intrusive relations, suggest that these plutons are coeval.

Hornblende alkali-feldspar granite

A small pluton of grayish, orange-pink hornblende alkali-feldspar granite (afh) underlies prominent hills along the west border of Jibal Aja, near the southeast corner of the Al Hufayr quadrangle. The pluton covers about 6 km^2 in the quadrangle and extends into the adjacent Al Qasr quadrangle.

The hornblende alkali-feldspar granite (fig. 2C) is medium grained and allotriomorphic equigranular. Its felsic components are plagioclase, quartz, and potassium feldspar (7, 32, and 60 percent, respectively). Plagioclase forms anhedral interstitial grains, as much as 2 mm long, that are albite twinned. Quartz is weakly recrystallized and forms anhedral grains as much as 2 mm in diameter. Potassium feldspar forms subhedral, Carlsbad-twinned grains as much as 4 mm long that are strongly perthitic. Trace amounts of green biotite, opaque oxides, zircon, apatite, and fluorite were also identified.

Granite

Granite (gr) crops out in a very limited area north of Jibal Aja at the southwest end of Jabal an Nihadah. The yellowish-gray granite may be country rock into which the adjacent porphyritic alkali granite was emplaced.

The granite (fig. 2C) is fine grained, allotriomorphic granular and porphyritic. Its felsic components are plagioclase, quartz, and potassium feldspar (24, 24, and 47 percent, respectively). Quartz forms anhedral grains up to 0.5 mm in diameter. Potassium feldspar is sercitized and forms anhedral grains as much as 2 mm long. Blocky phenocrysts of plagioclase are anhedral to subhedral and as much as 1 cm long. Anhedral hornblende forms about 5 percent of the rock and occurs in grains as much as 1 mm long that are pleochroic from pale yellow brown to brownish green. Trace amounts of biotite, that is pleochroic from pale yellow brown to dark reddish brown, sphene, apatite, and opaque oxides were also identified. The fine-grain size and allotriomorphic granular texture of this rock suggest that the magma represented by this rock was quenched.

Quartz syenite

An area of at least 20 km^2 located west and southwest of Umm al Qulban is underlain by a quartz syenite (qs) that is cut by many dikes. The quartz syenite is pinkish gray and forms a number of isolated inselbergs emergent through sand of the An Nafud.

The quartz syenite (fig. 2B) is fine to medium grained and allotriomorphic inequigranular. Its felsic components are plagioclase, quartz, and potassium feldspar (22, 15, and 60 percent, respectively, for a single sample). Quartz forms weakly recrystallized aggregates as much as 1 mm in diameter.

Potassium feldspar forms subhedral, strongly perthitic grains as much as 3.5 mm long. Plagioclase forms anhedral, interstitial grains that are as much as 0.5 mm long. The quartz syenite has a color index of 3 and includes the mafic silicates aegerine-augite, arfvedsonite, and aenigmatite. Aegerine-augite forms subhedral grains as much as 1 mm in diameter that are pleochroic from emerald green to very dark green. Arfvedsonite forms anhedral grains as much as 2.5 mm long that are pleochroic from greenish brown to bluish green. Aenigmatite forms spindle-shaped grains as much as 2 mm long that are very dark red. A trace amount of elpidite (sodium- zirconium silicate) was also identified.

Uwayrid alkali granite

A pluton composed of pinkish-gray alkali granite crops out in an area of about 30 km^2 at the north end of Jibal Aja. The pluton is herein informally named the Uwayrid alkali granite (uag) for prominent exposures in Jabal Uwayrid. The pluton is cut by a number of prominent dusky red dikes as much as 0.5 m in width that trend approximately east-west. The alkali granite is considered to be a mass of roof rock that was intruded by the members of the Aja suite.

The alkali granite (fig. 2C) is coarse grained and hypidiomorphic inequigranular. Its felsic constituents are plagioclase, quartz, and potassium feldspar (7, 30, and 59 per cent, respectively). Quartz forms anhedral grains as much as 4 mm in diameter that are incipiently recrystallized in most samples. Potassium feldspar forms subhedral grains, as much as 6 mm long, that are sericitized and perthitic. Some are weakly recrystallized. Plagioclase forms rare anhedral grains, as much as 2 mm long, that occur interstitially. The color index of the alkali granite is 4. Aegerine-augite, the principal mafic silicate in this rock, forms anhedral granular aggregates as much as 4 mm in diameter that are emerald green. The pyroxene is incipiently replaced by gray-green to pale-bluish-green kataphorite. Trace amounts of opaque oxides, zircon, allanite, and reddish brown biotite were identified.

Alkali-feldspar granite

A pluton composed of grayish, orange-pink alkali-feldspar granite (afg) crops out in isolated inselbergs emergent through the sand of the An Nafud in an area of about 6 km^2 located about 10 km west of Qina. The pluton is cut by dikes that trend east-west across this area.

The alkali-feldspar granite (fig. 2B) is medium grained and hypidiomorphic inequigranular. Its felsic components are plagioclase, quartz, and potassium feldspar (4, 19, and 69 per cent respectively). Quartz forms anhedral grains, as much as 3 mm in diameter, that are weakly fractured. Potassium feldspar forms anhedral to subhedral grains, as much as 7 mm long, that are perthitic and sericitized. Rare plagioclase crystals are anhedral, interstitial, and about 2 mm long. The color index of the alkali-feldspar granite is 8. Kataphorite is the principal mafic silicate and forms anhedral to subhedral grains, as much as 2 mm long, that are pleochroic from pale yellow green to moderate brownish green. Minor amounts of opaque oxides, associated with kataphorite, allanite, and zircon were also identified.

The hornblende alkali-feldspar granite, granite, quartz syenite, Uwayrid alkali granite, and alkali-feldspar granite are considered to be coeval. They share similarities of composition, lack of deformation, and intrusive relations with both dikes and members of the Aja suite. Most of these plutons are cut by dikes and occur as xenolithic masses within the Aja suite. These features suggest that these plutons are older than those of the Aja suite despite the compositional similarity that exists between these plutons and those of the Aja suite.

Dikes

Several prominent sets of vertical, felsic dikes occur within the Al Hufayr quadrangle. A dike swarm that forms between 50 and 90 percent of the penetrated outcrops, trends approximately east-west and forms most of the hills west of Qina and Umm al Qulban. The inselbergs north of Jabal Saq and Jabal Khasab are also composed of dikes of this swarm. Dike density is so great in some places that host rock is minor. The Uwayrid alkali granite located at the north end of Jibal Aja is cut by two different sets of dikes. One set of dikes weathers brick red and appears to be very highly evolved, whereas dikes of the other set weather dark greenish-black and seem to be relatively mafic. No attempt was made to discriminate the dikes in the quadrangle on the basis of composition because most dikes were not visited. The descriptions that follow outline the essential petrographic character of the two different dike sets that penetrate rocks of the Al Hufayr quadrangle. The rocks of the Aja suite are not intruded by these dikes and are presumed to be younger than the dikes.

Most of the dikes in the quadrangle are rhyolitic in composition and the presence of soda pyriboles indicates a peralkaline affinity. These dikes are porphyritic. They contain as much as 10 percent subhedral to euhedral phenocrysts of quartz and potassium feldspar in a very fine grained micrographic matrix composed of quartz and alkali feldspar. Spherulitic overgrowths, as much as 3 mm in diameter, surround phenocrysts in some samples. Potassium feldspar phenocrysts are as much as 3 mm long, are perthitic, and are altered to sericite and hematite. Quartz forms phenocrysts that are as much as 2 mm in diameter. Subhedral grains of aegerine-augite, as much as 0.5 mm long, form between 0 and 10 percent of the felsic dikes and occur in granular aggregates. Arfvedsonite is a less common component of these dikes. Trace amounts of zircon and opaque oxides were also identified.

The mafic dikes are inequigranular and consist of subhedral plagioclase and anhedral hornblende. Plagioclase grains, as much as 2 mm long, are zoned and partially altered to sericite. Anhedral grains of hornblende, as much as 0.5 mm long, occur in granular clusters. The hornblende is pleochroic from very pale yellow to pale brownish green. Opaque oxides form about 5 percent of these dikes. Trace amounts of biotite, after hornblende, and apatite were also observed.

Aja suite

The Jibal Aja batholith, an area of about 35 by 85 km, is composed of a cogenetic suite of coarse-grained hypersolvus peralkaline granite, porphyritc micrographic granophyre, and rhyolite. The name is derived from Jibal Aja, a long high ridge of granite located west of the city of Ha'il (fig. 1). The batholith was named by Stoeser and Elliott (1980) and subsequently used by Kellogg (1983) in the adjacent Qufar quadrangle. The Aja suite is subdivided into rim and core subunits. The rim units are the porphyritic, aegerine-augite, kataphorite, and leuco-alkali granites and the core units are the hornblende and core granophyres and the rhyolite.

Porphyritic alkali granite

Grayish, orange-pink porphyritic alkali granite (ajp) is the innermost rim granite and forms a rim around the core granophyre. This unit forms a prominent set of hills along the western and northern boundary of Jibal Aja.

The alkali granite (fig. 2A) is medium grained, hypidiomorphic granular, and contains phenocrysts of potassium feldspar. The micrographic intergrowth of quartz and alkali feldspar is discernible in some samples. Its felsic components are plagioclase, quartz, and potassium feldspar (5, 25, and 63 percent, respectively). Quartz forms anhedral grains as much as 4 mm in diameter. Weakly sericitized, subhedral potassium feldspar phenocrysts, as much as 1 cm long, are perthitic and Carlsbad twinned. Rare grains of plagioclase, less than 2 mm long, are anhedral and interstitial. The color index of the porphyritic alkali granite is 7. Arfvedsonite and aegerine-augite are the principal mafic silicates, however, the relative contents of these two minerals is highly variable between samples. Arfvedsonite forms subhedral grains, as much as 3 mm long, that are pleochroic from greenish tan to mottled green and dark blue. Aegerine-augite forms subhedral grains, as much as 2 mm long, that are emerald green. Trace amounts of opaque oxides, zircon and fluorite were identified.

The porphyritic alkali granite clearly intrudes the Uwayrid alkali granite. The contact between these two units is subhorizontal and again suggests that the Uwayrid alkali granite represents a slab of roof rock into which the porphyritic alkali granite was emplaced.

Aegerine-augite alkali granite

The western outer rim of Jibal Aja is composed of a narrow band of aegerine-augite alkali granite (aja). This grayish, orange-pink rock forms a prominent ridge at the west edge of the Aja suite where it underlies an area of about 5 km^2.

The aegerine-augite alkali granite (fig. 2C) is medium grained and hypidiomorphic inequigranular. Its felsic components are plagioclase, quartz, and potassium feldspar (7, 35, and 43 per cent, respectively). Quartz forms anhedral grains as much as 4 mm in diameter. Potassium feldspar forms subhedral, perthitic, Carlsbad-twinned grains as much as 6 mm long. Rare plagioclase grains are anhedral, interstitial, and less than 2 mm long. The color index of the aegerine-augite alkali granite is 15. Aegerine-augite is the principal mafic silicate although arfvedsonite was also identified. Aegerine-augite forms anhedral to subhedral grains, as much as 5 mm long, that are pleochroic from pale yellow green to mottled blue green. Arfvedsonite forms anhedral grains, that locally replace aegerine-augite, and are pleochroic from grayish green to blue green. Minor purple fluorite and elpidite were identified in some samples.

Kataphorite alkali granite

The region north of Jibal Aja, including Jabal an Nihadah, is composed of grayish, orange-pink kataphorite alkali granite (ajk) that forms prominent whalebacks. The kataphorite alkali granite forms the outermost rim of the Aja suite. This pluton is penetrated by several very prominent brick-red weathering felsic dikes that trend east-west.

The kataphorite alkali granite (fig. 2B) is medium to coarse grained and hypidiomorphic inequigranular. Its felsic components are plagioclase, quartz, and potassium feldspar (3, 30, and 61 percent, respectively). Quartz forms anhedral grains as much as 4 mm in diameter. Blocky, Carlsbad-twinned, perthitic potassium feldspar crystals are anhedral to subhedral, weakly sericitized, and as much as 8 mm long. Rare plagioclase crystals are anhedral, interstitial, and not more than 1 mm long. The color index of the kataphorite alkali granite is 6. Kataphorite, the only mafic silicate found in this rock, forms anhedral grains as much as 2.5 mm long that are pleochroic from yellow brown to brownish green. Trace amounts of opaque oxides, zircon, allanite, and purple fluorite were identified associated with kataphorite grains. Trace amounts of biotite appear to replace kataphorite.

Because of the lithologic and structural similarities that exist between the kataphorite, porphyritic, and aegerine-augite alkali granites, and because all are rim granites around the core granophyres of the Aja suite, they are considered to be approximately coeval. The intrusive relations of these rocks plus the absence of dikes and cataclastic features indicate that these rocks are younger than those previously described.

Leuco-alkali granite

A small pluton composed of yellowish-gray leuco-alkali granite (ajl) crops over about 7 km^2 along the west rim of Jibal Aja just west of the quadrangle's southeast corner. The leuco-alkali granite forms prominent hills.

The leuco-alkali granite (fig. 2C) is medium grained and hypidiomorphic inequigranular. Its felsic components are plagioclase, quartz, and potassium feldspar (5, 23, and 69 percent, respectively). Quartz forms anhedral grains, as much as 2.5 mm in diameter, that are weakly fractured. Subhedral potassium feldspar grains, as much as 4 mm long, are perthitic and weakly altered to sericite. Rare anhedral plagioclase crystals are interstitial and less than 1 mm long. The color index of the leuco-alkali granite is 3. Aegerine-augite is the principal mafic silicate, although a trace amount of arfvedsonite was identified. Aegerine-augite forms anhedral grains, as much as 1 mm in diameter, that are emerald green. Arfvedsonite forms anhedral grains, less than 0.5 mm long, that are pleochroic from pale greenish gray to blue green. Trace amounts of zircon, fluorite, and opaque oxides were found associated with grains of aegerine-augite. The leuco-alkali granite is considered to be younger than the rim granites of the Aja suite because it appears to truncate the porphyritic alkali granite.

Hornblende granophyre

An area of about 5 km^2 along the eastern boundary of the quadrangle, just north of its southeast corner, is underlain by a pale-yellow-brown hornblende granophyre (ajw). The outcrop pattern of the granophyre is that of a very large dike. In the field, the hornblende granophyre is distinguished from the surrounding granophyre on the basis of its color.

The hornblende granophyre (fig. 2A) is fine to medium grained and allotriomorphic equigranular. The groundmass is composed of fine-grained quartz and alkali feldspar in micrographic intergrowth. Its felsic components are plagioclase, quartz, and potassium feldspar (2, 26, and 71 percent, respectively). Quartz forms anhedral grains as much as 2 mm in diameter. Perthitic potassium feldspar forms anhedral grains as much as 4 mm long that are partly altered to fine a grained mixture of hematite and sericite. Rare plagioclase grains form anhedral, interstitial grains that are less than 1 mm long. The color index of the hornblende granophyre is 1. Hornblende is the sole mafic silicate and occurs as anhedral grains, less than 0.8 mm in diameter, that are pleochroic from pale yellow to olive green. Trace amounts of opaque oxides, fluorite, zircon, and red-brown biotite were also identified.

Core granophyre

The interior of Jibal Aja in the Al Hufayr quadrangle is underlain by a micrographic alkali-feldspar granite, here informally referred to as the core granophyre (ajc). The granophyre is pale reddish brown and occupies an area of about 160 km^2 in the quadrangle. The granophyre forms prominent hills throughout its outcrop area. In the field, it is clear from distinct, but regionally untraceable contacts and color differences that there are multiple, compositionally similar, units within the core granophyre, but these were not mapped due to their lithologic similarity and complex intrusive relations.

The core granophyre (fig. 2B) is fine to medium grained and allotriomorphic granular. The groundmass is composed of fine-grained quartz and alkali feldspar in micrographic intergrowth. Quartz and potassium feldspar crystals give the granophyre an incipiently porphyritic texture in some samples. Its felsic components are plagioclase, quartz, and potassium feldspar (9, 24, and 65 percent, respectively). The scatter displayed on the quartz-alkali feldspar-plagioclase plot (fig. 2B) by samples of the granophyre probably does not represent true compositional variation within this unit, but may reflect the difficulties that arise in performing modal analyses of fine grained, micrographic rocks. Quartz forms rounded grains, as much as 1.5 mm in diameter, that are partially resorbed. Weakly perthitic potassium feldspar forms anhedral to subhedral crystals as much as 2.5 mm long that are Carlsbad twinned and weakly altered to sericite and stained reddish- pink by hematite. Rare plagioclase forms fine-grained anhedral grains that occur interstitially. The color index of the core granophyre is 2. Anhedral crystals of biotite, which are pleochroic from yellow brown to greenish-brown, are as much as 1 mm long, and are incipiently replaced by chlorite. Trace amounts of zircon, fluorite, and opaque oxides were also observed.

The hornblende granophyre is considered to be younger than the alkali granites that form the rim of Jibal Aja. The core granophyre, which surrounds the hornblende granophyre, intrudes the surrounding rim granites and therefore is considered younger. The hornblende granophyre is probably cogenetic with the enclosing core granophyre and together, and as evidenced by their textures these two units represent emplacement and the rapid cooling of magma in a near-surface environment. Their solidification occurred very late in the crystallization history of the Aja suite and involves crystallization of the magma at the core of the batholith following earlier crystallization of the rim alkali granites against relatively cool wall rock.

Rhyolite

A small intrusive rhyolite (ajr), characterized by hypabyssal textures, has intruded the core granophyre about 8 km from the southeast corner of the quadrangle. The grayish-red rhyolite forms a large dike-like feature that occupies about 3 km^2 in this area.

The rhyolite (fig. 2C) is fine grained, porphyritic, and allotriomorphic granular. The groundmass is composed of fine-grained quartz and alkali feldspar in micrographic intergrowth. The felsic components are quartz and plagioclase (16 and 84 percent, respectively). The apparent quartz-poor character of the rhyolite is probably not real, but reflects the difficulties encountered in performing accurate modal analyses on fine grained, micrographic rocks. Quartz forms rounded, resorbed phenocrysts as much as 1.5 mm in diameter. Potassium feldspar forms anhedral to subhedral phenocrysts, as much as 2.5 mm long, that are weakly perthitic. Trace amounts of opaque oxides, fluorite, zircon, and biotite, that forms fine grained anhedral crystals that are pleochroic from pale yellow to greenish tan, were also identified. Because the dike-like unit of rhyolite intrudes the core granophyre it is considered to be the youngest Precambrian rock in the quadrangle.

PALEOZOIC ROCKS

The Saq Sandstone (O€s) is a quartz arenite that rests unconformably on a gently inclined erosional surface of Precambrian rocks in the northern part of the quadrangle. Powers and others (1966) provide a good regional description of the Saq Sandstone and indicate that it probably represents Early Cambrian through Early Ordovician sedimentation. The Saq Sandstone crops out in two short hills in the northwest part of the quadrangle but, the contact between it and the underlying rocks is concealed by eolian sand. The sandstone is massively bedded although small-scale cross bedding was locally observed.

Within the map area the Saq Sandstone is homogeneous. Neither silty, conglomeratic, or shaley beds were observed, although these are reported elsewhere in the formation (Powers and others, 1966). A few beds that contain rounded milky quartz pebbles, as much as 2 cm in diameter, were identified. The sandstone is a moderately well sorted aggregate of medium to coarse, subangular to subrounded grains of monocrystalline quartz that show various degrees of strain and are cemented by carbonate. Polycrystalline quartz grains are sparse. The sandstone is relatively well compacted and is grain supported.

Carbonate cement forms between 20 and 30 percent of the sandstone; it is locally replaced by ferruginous material that gives the sandstone its reddish-brown color.

TERTIARY ALKALI BASALT

A small plug, approximately 200 m in diameter, of columnar jointed, holocrystalline alkali basalt (Tb) crops out near the southeast corner of the quadrangle. Emplacement of the plug within the Aja suite was probably controlled by a major fracture. Isolated plugs, cinder cones, and small remnants of flows occur in the adjacent Hail, Al Qasr, and Qufar quadrangles (fig. 1). No chemical analyses are available for samples of the plug in the Al Hufayr quadrangle, but analyses for two plugs in the Al Qasr quadrangle indicate that they are composed of alkali basalt (Stoeser and Elliott, 1984, unpub. data). Petrographic similarities between samples from the plugs in the Al Qasr quadrangle and samples from the plug in the Al Hufayr quadrangle suggest that the latter are also composed of alkali basalt.

The basalt is reddish brown and contains a moderate number of distinctive, elliptical peridotite xenoliths that are between 0.5 and 10 cm in diameter. Subhedral phenocrysts of olivine, as much as 1 mm in diameter, form five to ten percent of the basalt. Anhedral to subhedral phenocrysts of pale grayish-pink augite, as much as 0.4 mm in diameter, form about one percent of the rock. The phenocrysts are set in a very fine grained, cloudy, felted matrix composed of plagioclase, pyroxene, and opaque oxides. The peridotite xenoliths are principally composed of coarse-grained, anhedral olivine and include 5 to 10 percent coarse-grained, anhedral orthopyroxene and trace quantities of red-brown chromite in subhedral grains as much as 0.5 mm in diameter.

QUATERNARY SURFICIAL DEPOSITS

Evaporite deposits

Evaporite deposits (Qe) form in local depressions and in small, blocked drainages and appear as bright white areas on LANDSAT imagery and on aerial photographs. These silt- and fine sand-laden saline encrustations are not more than several meters in thickness and most accumulations are less than a meter thick. The largest of these deposits forms a playa that is located 5 km southeast of Al Hufayr.

Alluvium

Alluvium (Qal) is predominantly composed of moderately well sorted sand-size material in active wadi channels but also includes silt, pebbles, fine windblown material, and unconsolidated conglomeratic material in wadis, and minor amounts of colluvium and talus deposits outside active channels. Colluvium forms poorly sorted inactive slope wash and occurs in areas of moderate relief. Talus deposits are restricted to areas underlain by blocky weathering bedrock and high relief.

Alluvial fan deposits

Alluvial fan deposits (Qaf) are poorly sorted and restricted to aprons around Jibal Aja and Jabal Khasab. Coalescing alluvial fans, adjacent to mountain fronts and cut by major wadis, form aprons around the highlands. Laterally migrating distributary channels are incised several meters below the fan surface and are filled with poorly sorted material ranging from silt to boulder size.

Eolian sand

About 80 percent of the quadrangle is covered by well sorted eolian sand (Qes) that is part of the An Nafud, and Nafud as Sayf, a subregion of the larger An Nafud, the second largest sand sheet on the Arabian Peninsula. Most of the pale-yellowish-orange sand that forms the sand sheet is stabilized and sparsely vegetated. In some places, a layer not more than 30 m thick of less vegetated, active sand rests on top of at least 100 m of inactive sand. The sand is arranged in barchan dunes whose orientation indicate that the prevailing winds are from the southwest. Nafud as Sayf is composed of somewhat more reflectant sand than is found elsewhere in the An Nafud.

Pediment deposits

Three areas in the Al Hufayr quadrangle are covered by pediment deposits (Qp). These areas are teardrop-shaped depressions located in the lee of large bedrock hills within the An Nafud sand sheet. The bedrock hills funnel and accelerate winds over their summits and cause leeward sand to be removed, resulting in deflation hollows. The ground surface in these areas is covered by several meters of poorly sorted gravels and minor windborne material. These are assumed to be rock pediment surfaces on the basement that are covered by a thin veneer of alluvium.

STRUCTURE

The Jadid syenogranite is characterized by a cataclastic foliation and lineation. Quartz and feldspar are thoroughly recrystallized and the primary mafic silicates have been replaced by anhedral aggregates of biotite. The foliation and lineation preserved in this rock type depicts a deformation that occurred prior to deposition of the Hadn formation rocks and prior to emplacement of all other intrusive rocks in the quadrangle. This deformation is also recorded in some rocks found in the adjacent quadrangles. In particular, Kellogg (1983) and Kellogg and Stoeser (1984) describe gneissic foliation in older granitoid terrane in the Qufar and Hail quadrangles, respectively (fig. 1). Clearly, this event is of regional significance but little is known concerning the events that caused this deformation.

Several plutons whose geneses post-date that of the Jadid syenogranite are characterized by weakly developed cataclastic features, including incipiently recrystallized quartz and alteration of the mafic minerals. These features may reflect a less intense deformation that occurred subsequent to deformation of the Jadid syenogranite or during its waning stage.

The rocks that compose Jibal Aja are transected by several prominent joint sets. Small displacements observed along some of these surfaces indicate that they are actually microfaults. The faults and joints are characterized by localized silicified breccias with iron oxide coatings but little demonstrable offset is apparent. The two most well developed joint sets trend northeast and northwest, respectively. The prominent, silicified breccia fractures trend northeast, northwest, and west.

METAMORPHISM

The mineral assemblages found in the layered rocks of the Al Hufayr quadrangle indicate that these rocks were metamorphosed in very low grade conditions. The assemblage epidote, biotite, albite, and quartz typifies the Hadn formation rocks in the Al Hufayr quadrangle. This assemblage is characteristic of lower greenschist facies metamorphism. In addition, primary volcanic textural features, characteristic of these rocks, are completely preserved. As pointed out by Quick (1983) the mineral assemblage observed in the Hadn formation rocks may be a result of autometamorphism which accompanied their deposition and lithification and may not be indicative of low grade regional metamorphism.

GEOCHRONOLOGY

Radiometric dating studies are just beginning in the northeast Arabian Shield and limited data exist for rocks in the Al Hufayr quadrangle. Episodes of magma genesis in the northeastern Arabian Shield are generally considered to be bimodally distributed; magmas were principally generated approximately 680 Ma ago and 620 Ma ago, although some highly evolved magmas that solidified to plutons composed of alkali-feldspar granite and alkali granite were generated between about 580 and 570 Ma ago (Baubron and others, 1976; Calvez and others, 1983; C.E. Hedge oral communication, 1983). The intrusive rocks in the Al Hufayr quadrangle, particularly those of the Aja suite are unusual, because the majority of them are probably the result of magma genesis that occurred between 580 and 570 Ma ago.

Aleinikoff and others (1984) report a U-Pb zircon age of 566 Ma for a sample from the outer rim alkali granite of the Aja suite in the Al Qasr quadrangle. This unit is probably correlative with the aegerine-augite alkali granite (aja) in the Al Hufayr quadrangle. No other radiometric ages are available for the intrusive rocks of the Al Hufayr quadrangle but age relations, composition, and emplacement style suggest that magmas represented by plutons of the Aja suite were generated at about this time. The compositional similarity that exists among the plutons of the Aja suite and the alkali-feldspar granite (afg), Uwayrid alkali granite (uag), quartz syenite (qs), granite (gr), and hornblende alkali-feldspar granite (afh) might suggest that all of these rocks are approximately coeval. The afg, uag, qs, gr, and afh plutons are found as large xenolithic masses within the Aja suite and (or) are cut by numerous dikes of a swarm that does not penetrate the plutons of the Aja suite. These plutons represent highly evolved magmas, characterized by either a peralkaline or a peraluminous affinity, that were generated before the Aja suite. These plutons are in turn younger than a group of less evolved plutons including gabbro (gb), biotite monzogranite (mgb), biotite-hornblende monzogranite (bhm), and syenogranite (sg), some of which are found as large xenolithic masses within the Aja suite and(or) are cut by dikes and(or) are characterized by weakly developed cataclastic textures. The composition, textures, and emplacement style of all plutons in the quadrangle, except those that compose the Aja suite, may represent magma genesis that elsewhere in the northeast Shield is considered to have occurred 620 Ma ago. The Jadid syenogranite (jsg) is intensely deformed and is probably older than the other rocks in the quadrangle. It may be one of a set of plutons in the northeast Shield that represents magma genesis 680 Ma ago.

Provisional constraints may be placed on the age of the Hadn formation using the results of rubidium/strontium isotopic data produced by R.J. Fleck (written communication, 1982). Data for samples of the Hadn formation collected in the Al Qasr quadrangle yield a best-fit isochron that corresponds to an age of about 613 Ma. The Hadn formation is therefore roughly coeval with the intrusive rocks generated in the northeast Shield approximately 620 Ma ago. The Hadn formation rocks and the intrusive rocks hypothesized to be approximately coeval pre-date the Aja suite rocks but are younger than the Jadid syenogranite.

Potassium-argon ages of about 15 and 19 to 20 Ma are reported by R.J. Fleck (written communication, 1982) for two basaltic plugs in the Al Qasr quadrangle and an age of 23.4 Ma is reported by Kellogg (1983) for a remnant of a basaltic flow in the Qufar quadrangle. Therefore, the alkali basalt plug in the Al Hufayr quadrangle is assumed to be Miocene in age.

GEOCHEMISTRY AND PETROGENESIS

Metamorphic rocks

A major element chemical analysis and CIPW normative composition for a sample of the porphyritic rhyolite flow rock which is a major constituent of the Hadn formation is presented in table 1. The sample is characteristic of the unit and was analyzed to document the composition of these rocks and to aid in their chemical classification. The sample is subalkaline as determined by Na_2O+K_2O versus SiO_2; it contains 9.00 percent Na_2O+K_2O at 74.6 percent SiO_2. The Al_2O_3 and normative plagioclase contents of the sample, 12.5 and 98 percent, respectively, indicate that it has a calc- alkaline affinity (Irvine and Baragar, 1971). A plot of normative color index versus normative plagioclase composition (fig. 3) indicates that the sample is composed of rhyolite. The relative proportions of normative an, ab, and or indicate that this rock is not part of either K_2O- or Na_2O-enriched volcanic series (Irvine and Baragar, 1971).

Intrusive rocks

The major- and rare-earth element chemistry of the principal intrusive rocks in the quadrangle is presented in tables 2 and 3, respectively. Major element chemical analyses for selected plutons in the Al Hufayr quadrangle indicate that the kataphorite, porphyritic, and aegerine-augite alkali granites, the alkali-feldspar granite, hornblende granophyre, and alkali granite are peralkaline as defined by Shand (1951). The remainder of the plutons for which analyses were obtained are metaluminous, although the single sample of biotite monzogranite is very nearly peraluminous (Shand, 1951).

Results of the major element analyses are plotted on the normative quartz-albite-orthoclase (Q-ab-or) ternary diagram (fig. 4) and compared to minimum melting compositions in the experimental system $SiO_2-KAlSi_3O_8-NaAlSi_3O_8-H_2O$ because the phase equilibria determined for this system are grossly applicable to highly evolved granitoid rocks such as those that crop out in the quadrangle. Phase relations displayed on figure 4 are not applicable to rocks having differentiation indices less than about 90 because such rocks contain significant amounts of components not considered on this ternary diagram.

Field, petrographic, and composition relations indicate that solidification of the magma represented by the rocks of the Aja suite commenced with crystallization in the alkali feldspar field (fig. 4). Petrologic considerations indicate that crystallization caused the composition of the remaining liquid to evolve away from the composition of the alkali feldspar that was crystallizing and towards the Q apex of the ternary diagram and the granite minimum composition appropriate to the prevailing conditions of pressure. The composition of the remaining magma became increasingly peralkaline because alkali feldspar has an agpaitic ratio, molar ratio $(Na_2O+K_2O)/Al_2O_3$, less than one. The compositional variation displayed by the porphyritic and kataphorite alkali granites is consistent with their being samples of a larger, parent magma that continued to evolve following their emplacement. The culmination of the trend toward increasing peralkalinity is depicted by the composition of the aegrine-augite alkali granite. This is the most peralkaline component of the suite and its composition, approximately coincident with the cotectic composition that prevails for crystallization when P(total) = $P(H_2O)$ = 50 millipascals (mPa) or 0.5 kilobar (kb) suggests that the magma represented by the aegerine-augite alkali granite crystallized at a depth not greater than 2 km. The strongly peralkaline composition of the magma represented by this pluton favored crystallization of peralkaline mafic silicates including aegerine-augite, arfvedsonite, and kataphorite.

The micrographic texture characteristic of the core granophyre and the fact that compositions for samples of this pluton cluster around the 50 mPa cotectic is consistent with solidification of the magma represented by this pluton at a depth not greater than 2 km. Crystallization of soda pyriboles from the magma represented by the aegerine-augite alkali granite quite effectively extracted the alkali components from the magma, thereby driving the composition of the remaining silicate liquid toward a nonperalkaline composition. The nonperalkaline, that is metaluminous, composition of the core granophyre and the absence of soda pyriboles in the core granophyre are a result of the crystallization and removal, perhaps by filter pressing or crystal settling, of soda pyriboles from silicate liquid remaining in the parent magma chamber.

Table 1.—Major element analyses and CIPW norms (calculated for analyses normalized to 100 percent, anhydrous) for selected volcanic and dike rocks in the Al Hufayr quadrangle

Analyses performed by X-ray Assay Laboratories Ltd., Ontario, Canada. All determinations by X-ray fluorescence, except FeO by wet chemistry. FeO/Fe_2O_3 ratio adjusted using guidelines proposed by Irvine and Baragar (1971) prior to norm calculation. All values in weight percent

Unit	Hadn formation rhyolite	Dacite dike
Sample number	128263	128266
Latitude (27° N.)	34'48"	42'05"
Longitude (41° E.)	13'58"	07'58"
	Chemical analyses	
SiO_2	74.6	66.3
Al_2O_3	12.5	13.3
Fe_2O_3	0.79	1.41
FeO	.40	3.50
MgO	.16	0.56
CaO	.20	2.00
Na_2O	4.23	3.81
K_2O	4.77	4.89
H_2O*	.23	1.16
TiO_2	.17	.61
P_2O_5	.03	.21
MnO	.04	.09
Total	98.12	97.84
	CIPW norms	
Q	31.8	20.4
C	0.1	-
or	28.8	29.9
ab	36.6	33.3
an	.8	4.9
wo	-	1.7
en	.4	1.8
fs	-	4.2
mt	1.0	2.1
il	.3	1.2
ap	.1	0.5

* H_2O is loss on ignition

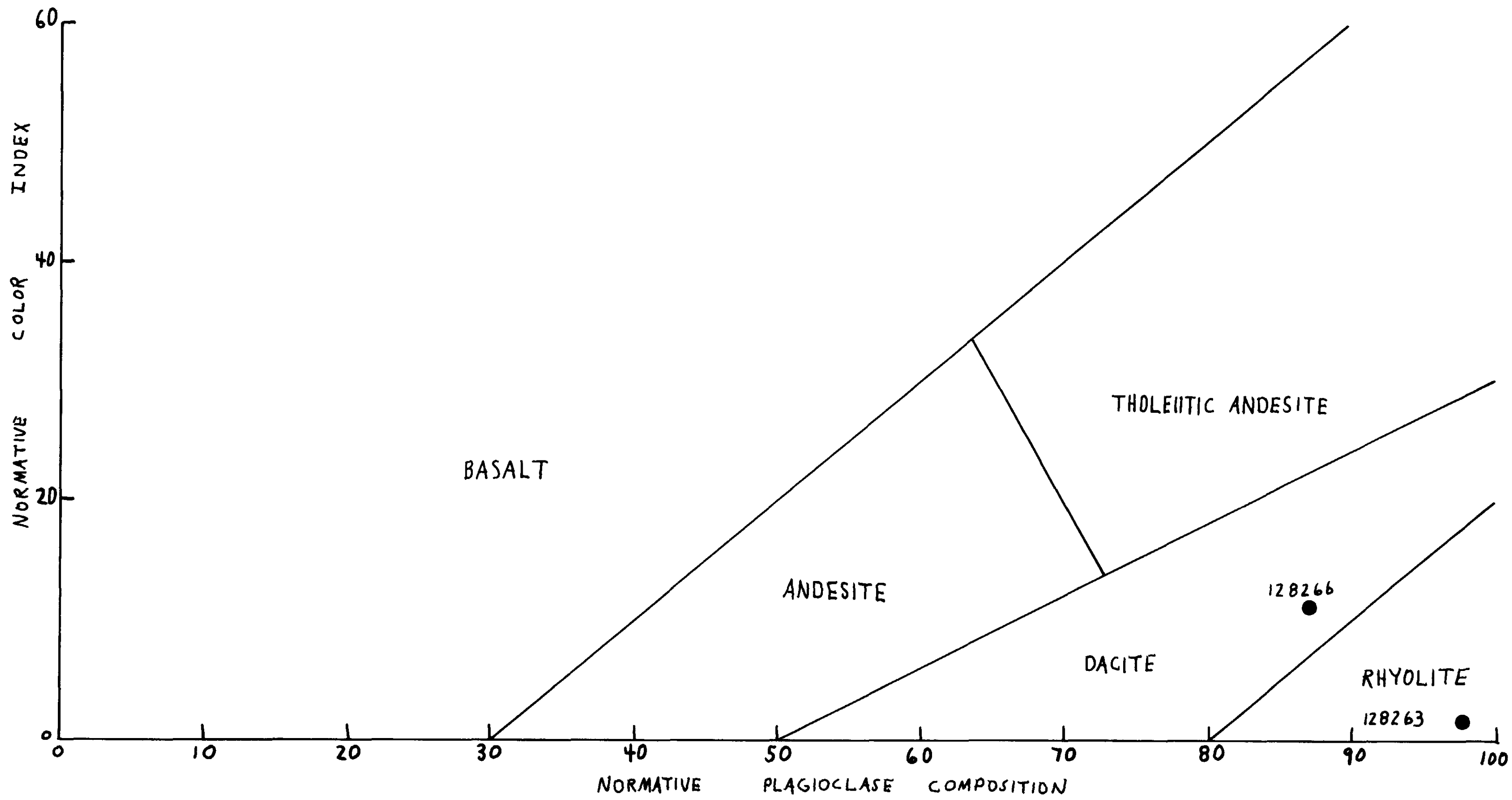


Figure 3.—Normative color index (=ol+hy+di+mt+il+hm) versus normative plagioclase composition (=an x 100/(an+ab+5/3ne)) variation diagram for classification of volcanic and dike rocks (Irvine and Baragar, 1971). Sample locations are given in table 1.

Table 2.—Major element analyses and CIPW norms (calculated for analyses normalized to 100 percent, anhydrous) for selected intrusive rocks in the Al Hufayr quadrangle

Analyses performed by X-ray Assay Laboratories Ltd., Ontario, Canada, except as noted. All determinations by X-ray fluorescence, except FeO by wet chemistry. All values in weight percent

Pluton	Kataphorite alkali granite		Alkali-feldspar granite	Syenogranite	Hornblende granophyre	Jadid Syenogranite	Monzogranite	Biotite monzogranite	Uwayrid alkali granite	
Sample number	128022	128630	128267	128218	128250	128262	128264	155158	128628	128631
Latitude (27° N.)	36'56"	43'39"	47'13"	37'09"	35'05"	31'00"	42'05"	38'16"	39'53"	38'53"
Longitude (41° E.)	19'59"	29'13"	20'22"	05'40"	29'45"	15'56"	07'58"	28'01"	28'28"	25'12"
					Chemical analyses					
SiO_2	70.9	71.5	70.3	70.7	74.8	72.0	71.7	77.1	71.8	73.2
Al_2O_3	12.7	12.5	13.0	14.7	12.0	13.8	14.0	12.0	12.2	12.4
Fe_2O_3	2.37	2.25	1.22	0.98	1.22	1.08	0.99	1.09	1.49	1.24
FeO	1.00	1.20	2.40	.60	0.10	0.60	1.00	0.54	1.30	1.60
MgO	0.31	0.21	0.26	.20	.17	.20	.56	.05	0.24	0.23
CaO	.84	.78	.90	.60	.40	.92	1.42	.20	.76	.67
Na_2O	4.40	4.43	4.64	5.68	4.08	4.72	4.71	4.33	4.59	4.49
K_2O	5.13	5.03	5.04	4.69	4.96	4.63	3.78	4.27	4.82	4.89
LOI**	.31	-	.39	.47	.70	.77	.54	.32	.61	.31
TiO_2	.37	.37	.41	.15	.13	.16	.28	.05	.30	.29
P_2O_5	.05	.05	.06	.03	.02	.04	.08	.05	.04	.04
MnO	.07	.08	.10	.07	.01	.03	.05	.01	.05	.05
Total	98.45	98.40	98.72	98.87	98.59	98.95	99.11	100.07	98.20	99.41
					CIPW norms					
Q	25.0	26.0	21.8	18.9	32.2	25.5	26.4	35.3	26.2	27.1
C	-	-	-	-	-	-	-	0.1	-	-
or	30.9	30.2	30.3	28.2	29.9	27.9	22.7	25.3	29.2	29.2
ab	37.5	36.9	39.5	48.8	34.8	40.7	40.4	36.7	36.8	36.9
an	-	-	-	0.8	-	2.8	6.0	.7	-	-
ac	0.4	1.1	0.4	-	0.4	-	-	-	2.6	1.3
ns	-	-	-	-	-	-	-	-	-	-
wo	1.6	1.5	1.7	.9	.8	0.6	0.3	-	1.5	1.3
en	.8	0.5	.7	.5	.4	.5	1.4	.1	0.6	0.6
fs	-	.2	3.1	.2	-	-	.7	-	1.5	1.9
mt	2.4	2.8	1.6	1.4	-	1.6	1.5	1.6	.9	1.2
hm	.6	-	-	-	1.1	-	-	-	-	-
il	.7	.7	.8	.3	.2	.3	.5	.1	.6	.6
ap	.1	.1	.1	.1	-	.1	.2	.1	.1	.1
					Agpaitic ratio					
	1.01	1.02	1.01	0.98	1.01	0.93	0.85	0.98	1.05	1.02

* Analyses performed by the Analytical Laboratories of the U.S. Geological Survey, Denver, Colorado (Stuckless, Van Trump, Bunker, and Bush, in press).

** LOI is loss on ignition

Table 2.—Major element analyses and CIPW norms (calculated for analyses normalized to 100 percent, anhydrous) for selected intrusive rocks in the Al Hufayr quadrangle—Continued

Pluton	Core granophyre					Porphyritic alkali granite		Aegerine-augite alkali granite	
Sample number	128251	128587	128634	155138*	155139*	128635	155137*	128637	155138
Latitude (27° N.)	35'05"	30'58"	36'59"	35'58"	35'17"	37'06"	36'05"	30'41"	37'39"
Longitude (41° E.)	29'33"	22'45"	23'04"	23'51"	24'13"	22'58"	22'45"	20'10"	21'46"
				Chemical analyses					
SiO_2	75.2	74.5	75.0	77.7	78.1	70.2	71.5	72.5	77.9
Al_2O_3	11.9	12.2	11.7	11.5	11.4	12.2	12.6	9.32	9.20
Fe_2O_3	0.54	1.49	1.26	0.70	0.56	3.14	3.72	5.15	3.09
FeO	.20	0.10	0.10	.45	.59	1.20	0.53	0.70	0.77
MgO	.13	.11	.10	.05	.05	0.29	.03	.27	.07
CaO	.49	.52	.52	.19	.27	.95	.89	.30	.19
Na_2O	3.63	4.33	3.97	3.40	3.35	4.82	3.56	5.00	3.38
K_2O	5.02	4.70	4.62	4.79	4.84	4.45	4.87	4.30	4.68
LOI**	1.16	.77	.77	.25	.46	.70	1.30	.39	.31
TiO_2	.12	.13	.11	.07	.06	.37	.42	.21	.16
P_2O_5	.02	.02	.01	.05	.05	.05	.05	.02	.05
MnO	.01	.05	.03	.01	.01	.11	.01	.11	.04
Total	98.42	98.92	98.19	99.15	99.72	98.48	99.46	98.27	99.87
				CIPW norms					
Q	34.8	31.2	34.3	39.7	39.6	25.0	30.9	31.1	41.8
C	-	-	-	0.5	0.3	-	-	-	-
or	30.5	28.3	28.0	28.6	28.8	20.9	29.3	26.0	27.8
ab	31.6	37.3	34.5	29.1	28.6	38.8	30.7	24.5	21.4
an	1.4	-	0.5	.6	1.0	-	4.1	-	-
ac	-	-	-	-	-	2.5	-	15.2	6.5
ns	-	-	-	-	-	-	-	0.3	-
wo	0.4	1.0	.9	-	-	1.9	-	.6	0.3
en	.3	0.3	.3	.1	.1	0.7	0.1	.7	.2
fs	-	-	-	.2	.5	-	-	1.2	.5
mt	.3	.1	.1	1.0	.8	3.2	.5	-	1.2
hm	.3	1.4	1.2	-	-	.1	3.4	-	-
il	.2	.3	.2	.1	.1	.7	.8	.4	.3
ap	-	-	-	.1	.1	.1	.1	.-	.1
				Agpaitic ratio					
	0.96	1.00	0.99	0.94	0.94	1.05	0.883	1.38	1.16

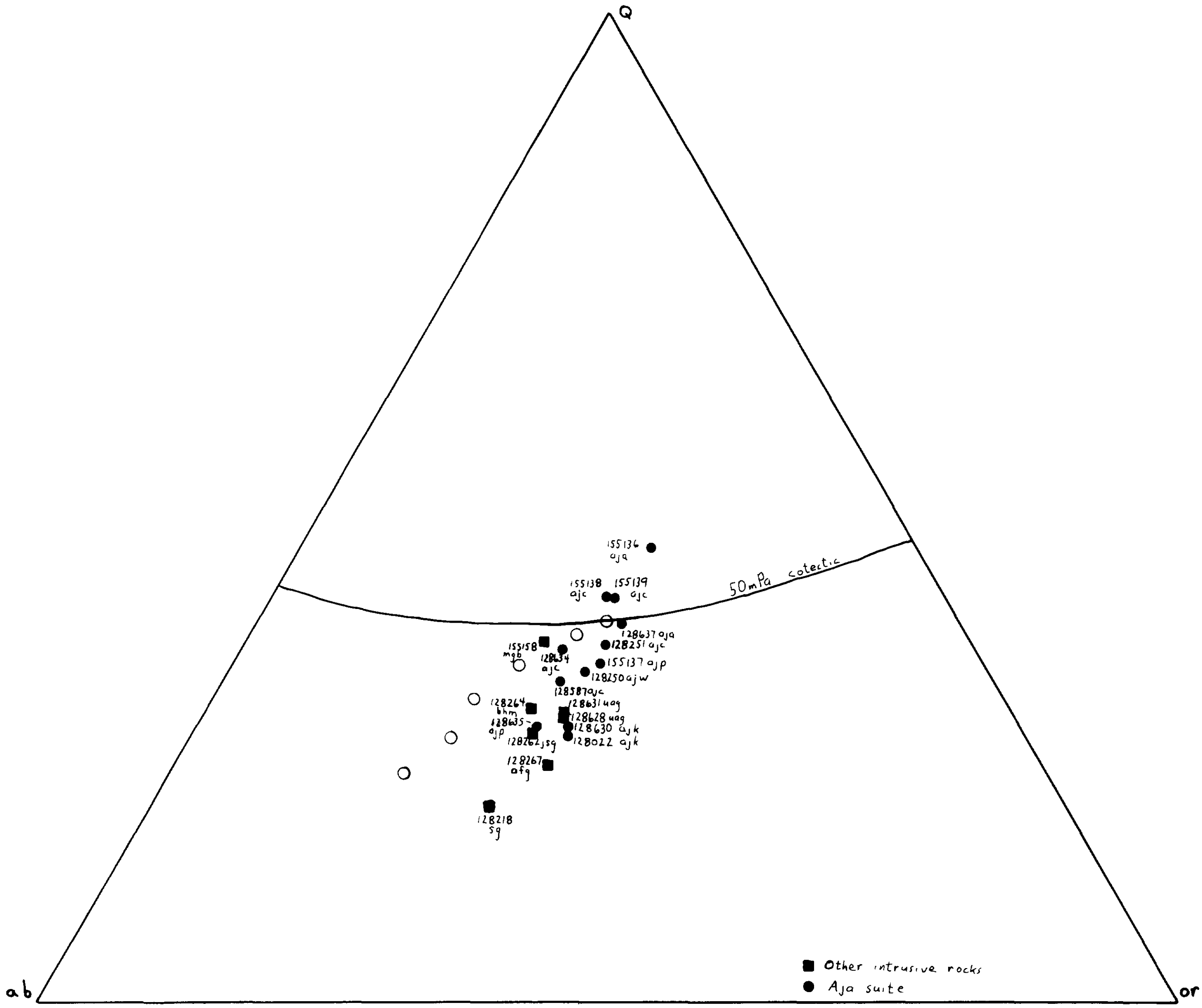


Figure 4.—Normative quartz-albite-orthoclase (Q-ab-or) ternary diagram showing the chemical composition of selected intrusive rocks of the Al Hufayr quadrangle. Sample locations are given in table 2. Unit symbols are given on plate 1. Open circles, from top right to bottom left, represent the minimum melting compositions in the experimental system SiO_2-$KAlSi_3O_8$-$NaAlSi_3O_8$-H_2O for $P(H_2O)$ = P(Total) = 50, 100, 200, 400, 500, 1,000 mPa (0.5, 1, 2, 4, 5, 10 Kbar), respectively (Winkler and others, 1975).

Intrusive relations indicate that the hornblende granophyre was emplaced after the core granophyre. The composition of the hornblende granophyre plots well below the 50 mPa cotectic, and therefore suggests crystallization at a significantly greater depth. However, cogenetic members of a suite, whose rocks are exposed at the same level should indicate crystallization at the same depth; therefore a mechanism by which the composition of the minimum melt composition can be changed towards those indicative of greater crystallization depths must be identified. The hornblende granophyre contains considerable fluorite and Manning (1981) has demonstrated that fluorine causes the composition of the alkali feldspar-quartz cotectic to move toward the alkali feldspar sideline of the Q-ab-or ternary diagram. The composition of the hornblende granophyre may indicate cotectic crystallization of a magma that contained about 0.25 percent dissolved fluorine, at a depth less than 2 km.

Q-ab-or compositions for the remaining samples analyzed allow some speculation on their geneses. The similarity that exists between the compositions of the Uwayrid alkali granite and the kataphorite and porphyritic alkali granites again suggests that the Uwayrid alkali granite is related to the Aja suite. However, it must, as indicated by the dikes that penetrate it, represent magmatism that occurred at a somewhat earlier time. The compositions of the Jadid syenogranite and the syenogranite relative to experimentally derived granite minimum compositions, and their moderately abundant modal fluorite contents, suggest that magmas they represent were fluorine rich. Alternatively they may have crystallized at somewhat greater depths. The latter is certainly possible because they are among the older rocks in the quadrangle. Yet another possibility is that they represent magmas in which the silicate liquid was evolving toward the appropriate granite minimum composition via noncotectic crystallization but did not experience separation of early formed crystals from the remaining liquid. If the composition of the biotite monzogranite sample is inferred to represent a cotectic composition, then the magma represented by that pluton appears to have crystallized in the same shallow depth range characteristic of the plutons that compose the Aja suite.

Rare-earth element (REE) analyses are presented in table 3 and chondrite-normalized REE patterns are plotted on figure 5 for samples of selected plutons in the Al Hufayr quadrangle. Data are for samples of the Aja suite, except for sample 155158, which is a sample of the biotite monzogranite. These data provide additional information concerning the genesis of the Aja suite. Chondrite-normalized patterns for samples of the Aja suite are parallel, that is fractionation of some REE elements relative to others is not apparent except for europium. Except for samples of the agerine-augite alkali granite, that contain unusually large abundances of the REE, the overall REE content of the Aja suite samples is nearly constant. The magnitude of the negative europium anomaly varies significantly among the various plutons of the Aja suite, however. Chondrite normalized patterns for rocks of the Aja suite are characterized by moderately negative slope, that is, the light REE are moderately enriched relative to the heavy REE and have negative europium anomalies of moderate magnitude. Patterns with these characteristics typify the postorogenic peralkaline plutons of the northeastern Arabian Shield (Stuckless, Knight, Van Trump, and Budahn, 1982). The negative slope is either a consequence of the stability of a heavy REE-enriched mineral, such as garnet, zircon, or hornblende in the residum from which the primary Aja suite magma evolved or of the crystallization and removal of one of these minerals from the magmas prior to their solidification.

The magnitude of the negative europium anomaly is approximately the same in samples of the porphyritic and kataphorite alkali granites and is larger in samples of the core granophyre and aegerine-augite alkali granite. In detail, the overall REE content is least in samples of the core granophyre, increases progressively in the kataphorite and porphyritic alkali granites, and is dramatically greater in samples of the aegerine-augite alkali granite. Fractionation of plagioclase is usually invoked to account for growth of negative europium anomalies (Hanson, 1978) and would cause an overall increase in the REE content of the remaining liquid but the near absence of plagioclase in samples of the Aja suite precludes its fractionation as a viable mechanism for increasing the negative europium anomaly.

The fractionation of alkali feldspar has an effect on the magnitude of a europium anomaly and causes the overall REE content of the remaining silicate liquid to increase. Drexler and others (1983) have demonstrated that the potassium feldspar-melt distribution coefficient for europium is dependent on the composition of the melt. The coefficient is greater than one for compositions with an agpaitic ratio less 1.0 to 1.1, so fractionation of alkali feldspar will increase the magnitude of a negative europium anomaly. The coefficient is less than one for compositions with an agpaitic ratio greater than 1.0 to 1.1, so fractionation of alkali feldspar will cause the magnitude of a negative europium anomaly to increase more slowly.

A magma with a REE content like that of the porphyritc alkali granite could be derived from one with a REE content like that of the kataphorite alkali granite by fractionation of alkali feldspar from the latter. The mineral-melt distribution coefficient for europium that would apply to the fractionation of alkali feldspar from a melt with the composition of the kataphorite alkali granite (average agpaitic ratio about 1.015) is very slightly greater than 1 (Drexler and others, 1983) so that the magnitude of the negative europium anomaly increased imperceptibly while the overall content of the remaining REE increased slightly.

Table 3.--Rare-earth element, uranium, and thorium analyses for selected intrusive rocks of the Al Hufayr quadrangle

Analyses by X-ray Assay Laboratories Ltd. Ontario, Canada, except as noted. All determinations by neutron activation, except uranium by delayed neutron counting

Pluton	Kataphorite alkali granite		Hornblende granophyre	Core granophyre		
Sample number	128022	128630	128250	128251	155138*	155139*
			Chemical analyses			
La	80	41	78	76	44	48
Ce	157	89	157	153	92	96
Nd	65	43	59	57	37	41
Sm	13.0	9.3	13.0	13.0	7.7	9.2
Eu	1.15	1.00	0.80	0.60	0.35	0.37
Tb	1.57	1.20	1.80	1.80	1.34	1.68
Dy	8.8	7.3	11.6	11.6	8.3	11.3
Yb	4.5	4.1	6.9	6.7	4.6	8.2
Lu	0.73	0.63	1.06	.99	.67	1.25
Th	12.0	9.2	26.0	25.0	17.1	28.9
U	3.6	2.6	8.4	9.1	6.5	10.4

Pluton	Porphyritic alkali granite		Biotite monzogranite	Aegerine-augite alkali granite	
Sample number	128635	155137*	155158*	128637	155136*
			Chemical analyses		
La	87	90	32	315	99
Ce	184	189	77	586	222
Nd	85	89	41	225	104
Sm	18.0	16.5	10.7	50	21.3
Eu	2.07	2.10	0.15	2.60	1.12
Tb	2.00	2.30	1.97	6.14	2.93
Dy	12.6	13.1	12.1	32.9	17.9
Yb	7.6	6.3	5.1	17.0	9.5
Lu	1.14	0.95	.72	2.50	1.37
Th	11.0	11.0	30.8	46.0	15.6
U	4.3	3.3	12.9	14.7	3.7

* Analyses performed by the Analytical Laboratories of the U.S. Geological Survey, Denver, Colorado (Stuckless, Knight, Van Trump, and Budahn, 1982)

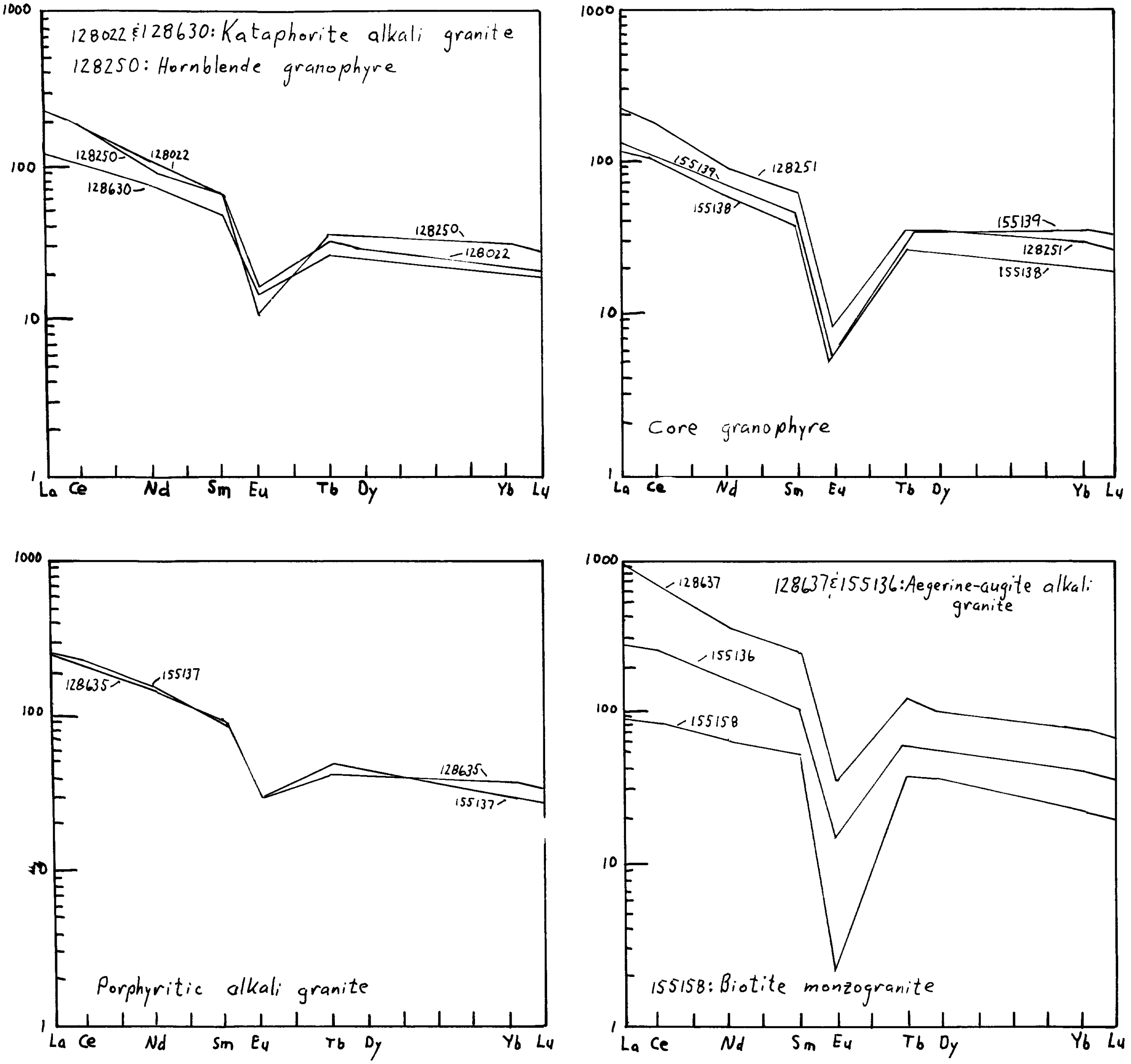


Figure 5.—Chondrite-normalized rare-earth element patterns for selected intrusive rocks of the Al Hufayr quadrangle.

A magma with a REE content like that of the aegerine-augite alkali granite could be derived from one with a REE content like that of the porphyritic alkali granite by extensive fractionation of alkali feldspar from the latter. An agpaitic ratio of 1.05, the ratio for sample 128635 (table 2) was used to establish the peralkalinity of the magma represented by the porphyritic alkali granite because the ratio for the other sample, 155137, is anomalously low, because the pluton contains large amounts of the soda pyriboles arfvedsonite and aegerine-augite, and suggests that the sample is altered and has lost Na_2O during weathering or late-stage magmatic processes. The fractionation would cause the composition of the remaining magma to become increasingly peralkaline, causing the value of the relevant distribution coefficient for europium to decrease and causing europium to be preferentially partitioned into the liquid phase. The growth of the negative europium anomaly was thereby retarded, relative to what it might have become in a metaluminous melt from which large quantities of alkali feldspar were being extracted, while the overall REE content of the remaining liquid increased dramatically. Drexler and others (1983) have further indicated that iron is also preferentially partitioned into the liquid phase as the liquid phase becomes more peralkaline. The fact that the aegerine-augite alkali granite is the most iron-rich member of the Aja suite and contains the greatest modal abundance of soda pyriboles may be a consequence of this phenomenon.

The final phase in the evolution of the remaining silicate liquid is represented by the core granophyre and is dominated by the crystallization and removal of a mineral that caused no change in the magnitude of the europium anomaly, maintained the slope of the pattern, and caused a dramatic overall reduction of the REE content. These changes could be the result of the crystallization and removal of a mineral characterized by mineral-melt distribution coefficients that are approximately the same for all REE but greater than 1 in order to achieve the observed decrease in the REE content of the remaining magma. No REE mineral-melt distribution coefficients are available for minerals with these characteristics. Soda pyriboles, for which these data are not readily available are abundant in the aegerine-augite alkali granite but are completely absent in the core granophyre; perhaps fractionation of these minerals is responsible for the observed changes in the REE content. Hornblende is characterized by REE mineral-melt distribution coefficients that approximate those necessary to effect the observed changes (Hanson, 1978) and perhaps the REE mineral-melt distribution coefficients for the soda pyriboles more closely approximate those that are necessary to achieve the observed overall REE depletion.

A single REE pattern for the hornblende granophyre is very similar to those for the core granophyre. This observation would seem to indicate that very little chemical evolution of the remaining liquid occurred between emplacement of the core and hornblende granophyres.

A single REE pattern for a sample of the xenolithic, nearly peraluminous, biotite monzogranite is a very gently negatively sloping pattern characterized by a large negative europium anomaly. This pattern is characteristic of highly evolved peraluminous granitoid rocks. The large negative europium anomaly is a consequence of crystallization and removal of plagioclase from the melt. Light REE depletion may be a consequence of the crystallization and removal of a light REE-enriched phase such as sphene, monazite, or allanite (Miller and Mittlefehldt (1982).

The plutons that compose the Aja suite represent samples of magma that depict the successive chemical evolution of the batholith-scale magma that solidified to the Aja suite. The chemical variation that is observed among the members of the suite must be a consequence of a discontinous process that involved magma evolution via separation of silicate liquid from earlier formed crystals, and emplacement of batches of magma whose compositions represent stages of the parent magma's chemical evolution.

ECONOMIC GEOLOGY

Mineral potential in the Al Hufayr quadrangle seems to be minimal. No ancient mines are known within the quadrangle and no mineralized areas were identified.

Twelve sediment samples were collected from wadis that drain Jibal Aja as part of the regional geochemical reconnaissance that is being conducted in the northeastern Arabian Shield by the U.S. Geological Survey. Geochemical data for heavy mineral concentrates of these samples were combined with that for approximately 600 samples collected in the adjacent quadrangles and statistically treated by factor analysis. The twelve samples are characterized by a distinctive association of elements that includes Nb, La, Y, Pb, Sn, and Be. This association is similar to that observed in wadi sediment samples collected from wadis that drain other peralkaline plutons in the northeastern Shield (Allen and others, 1983) and mimics the characteristic trace element chemistry of the source rock; the association does not necessarily correlate with high mineral potential.

In the adjacent Al Qasr quadrangle (fig. 1) massive fluorite was found in a shear zone in the core granophyre (Stoeser and Elliott, 1994, unpub. data). The potential for fluorite exists in the rocks of the Aja suite in the Al Hufayr quadrangle.

DATA STORAGE

Documents relating to this project have been archived in data file USGS-DF-04-13 (du Bray and Stoeser, 1984). This file consists of a sample locality map and documents the rock type encountered at each sample site.

No MODS localities exist within the Al Hufayr quadrangle nor were new localities that merit inclusion in MODS encountered. Inquiries regarding the MODS data bank may be made through the Office of the Technical Advisor, Saudi Arabian Deputy Ministry for Mineral Resources, Jiddah.

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